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Reference Frequency Transmission Over Optical Fiber

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A 100-MHz reference frequency from a hydrogen maser frequency standard has been transmitted via optical fiber over a 14-km distance with a measured stability of 1.5 $\times$ 10^{-15} *for 1000 seconds averaging time. This capability was demonstrated in a frequency distribution experiment performed in April, 1986. The reference frequency was transmitted over a single-mode fiber-optic link from Deep Space Station (DSS) 13 to DSS 12 and back to DSS 13.*

This article will discuss the background leading up to the experiemnt and the significance of stable reference frequency distribution in the Deep Space Network (DSN). It will also describe the experiment, including the fiber-optic link, the measurement method and equipment, and finally the results of the experiment.

I. Introduction

The Deep Space Network (DSN) has very stringent requirements for precise frequency and time. JPL uses hydrogen maser frequency standards in the DSN to meet these requirements. They are currently capable of stability performance at the level of better than one part in 10^{-15} over averaging intervals of 1000 seconds. The future goal for frequency stability in the DSN requires improvements of up to two orders of magnitude over the present capability.

Such stringent requirements demand the development of a new generation of ultrastable sources of frequency, such as heavy ion frequency standards. The performance level of these new standards will place extreme stability requirements on the transmission systems that must distribute these reference frequencies to the users.

Group delay variations occur in all cables and make ultrastable frequency distribution difficult. As the group delay changes in a cable it causes the frequency of a signal passing through the cable to be offset by an amount proportional to the rate of change. Temperature changes, atmospheric pressure changes, and bending of a cable produce these group delay changes in the cable that degrade the stability of a reference frequency transmitted through the cable. Temperature changes have, by far, the greatest effect on group delay and, therefore, cause most of the degradation in frequency stability of a signal passing through a cable.

Currently, coaxial cables are used to distribute precise reference frequencies from a single hydrogen maser within a station to a number of local users. It is clear, however, that the distribution of precise frequency and time from a centralized

location to remote users within an entire complex offers some attractive benefits. Such benefits include the possibility of arraying stations for experiments such as connected element interferometry, an economy in the number of frequency standards within the complex, and a redundancy in frequency standards. This latter feature will guarantee the availability of hydrogen masers during critical periods such as encounters, and will provide for the capability of continuous characterization of the performance of the frequency source.

JPL has recognized the advantages of an ultrastable distribution system for the past several years, and efforts have been underway to develop a technology to enable a centralized frequency and timing facility. Early in the inception of this concept it was recognized that optical fiber was the most effective media for this application. This is primarily because optical fiber has superior qualities with respect to stability, immunity to radio frequency interference (RFI) and electromagnetic interference (EMI) and ability to transmit high-frequency signals over tens of kilometers without repeaters.

JPL initiated development of fiber-optic distribution systems for precise time and frequency as a task in 1979. The initial efforts included a survey of the technological trends, acquisition and evaluation of components, and the determination of delay stability and cable losses. In the following years the scope of this effort expanded to include the installation of a 3-km experimental link at JPL, and the demonstration of analog signal and digital data transmission. Other accomplishments in the effort included the demonstration of frequency division multiplexing and two-way transmission in the same fiber.

Following this work, the effort was directed to the use of a negative feedback technique to stabilize the delay through the fiber (Refs. 2, 3). This resulted in a stability of a few parts in 10^{-16} for 1000 seconds averaging time over the stabilized 3-km link at JPL.

Transmitters, isolators, and techniques for 1300-nm systems were developed next and led to the installation of a cable to link DSS 12 and DSS 13 in the Goldstone Deep Space Communications Complex. This cable contains four multimode fibers, which were spliced and tested in 1983, and two experimental single-mode fibers. The multimode fiber in the 7-km cable became the first optical fiber link in the DSN, and has been used to demonstrate the replacement of microwave links between stations for the transmission of data, voice, television and time references.

After the installation of the single-mode fibers in the cable was completed, the magnitude of changes in group delay and rate of change of group delay in the cable had to be determined so an optimum electronic stabilizer, to be used to further stabilize the link, could be designed. The purpose of the experiment reported here was to determine these parameters and to measure the frequency stability of a signal passing through the unstabilized cable. The stability was measured with a frequency stability analyzer that was designed and fabricated at JPL.

After the measurements were completed the link was set up for one-way distribution of the signal from DSS 13 to DSS 12 to be used as the station reference for a planned coherent interferometry experiment.

II. Fiber-Optic System

A fiber-optic cable containing 6 fibers was buried between Deep Space Station (DSS) 13 and DSS 12, a distance of approximately 7 km. Two of the fibers in this cable are the first single-mode fibers manufactured by Corning Glass Works to be used in a nonmilitary installation. They have an 8.5-μm core diameter, 125-μm cladding diameter and are designed to operate at a 1300-nm wavelength. The experiment was performed on these fibers.

One of the first concerns in trying to achieve ultrastable frequency transmission through a cable is to ensure that the delay instabilities in the cable are minimized as much as is practical by such passive means as the location and the method of cable installation before electronic stabilizing systems are employed.

In order to minimize temperature variations, the cable was buried to a depth of 1.5 m, as deep as was practical with commercial equipment. The cable was plowed directly into the ground with a nonvibrating cable plow after the ground was preripped. This was to keep stresses on the cable to a minimum. Fusion splicing was used to avoid splice reflections that can reduce the effectiveness of a cable stabilizer.

The total loss in each of the two single-mode fibers is approximately 14 dB. This includes splice loss and a loss of 3 dB in a directional coupler at one end of the fiber. It also includes mismatch losses, due to differently sized fiber cores in the fibers in the cable and the fibers in the pigtails which have factory installed connectors.

A good fiber-optic cable, such as this one, has a temperature coefficient of delay of about 7 ppm/K (Ref. 1). The sensitivity to atmospheric pressure change has not been directly measured but appears to be quite small.

A commercial fiber-optic transmitter designed to transmit television signals was used. We modified the transmitter by

bypassing the filters and DC restorer circuit to make it operate with a 100-MHz sinewave. The transmitter uses a 1300-nm single-mode semiconductor laser that emits 0.5 mW of optical power into the optical fiber. It contains electronic circuitry to control the optical output power of the laser and to keep its temperature constant.

The receiver was designed and fabricated by personnel in the Time and Frequency Systems Research Group. It has 400-MHz bandwidth which results in good temperature stability, and long-term phase stability. It remains linear under the large signal conditions encountered in this application. This provides the maximum possible signal-to-noise ratio, and therefore the best short term phase noise.

A schematic of the receiver is shown in Fig. 1. It contains a PIN photodiode, a bias circuit, a decoupling circuit and a multimode fiber pigtail. The optical input is coupled to the PIN photodiode through a multimode optical fiber. The PIN photodiode is an Indium Gallium Arsenide (InGaAs) device. Biasing is provided by a low noise voltage source (Ref. 4) consisting of a constant current diode and a low noise zener diode. Two wideband transformers loaded with their characteristic impedances provide wideband high impedance decoupling to the photodiode. The output is coupled through an SMA RF connector to a low noise wideband amplifier with 50-ohms input impedance.

III. Fiber-Optic System Configuration

Figure 2 shows the fiber-optic link configuration used for the experiment. An RF power divider splits the RF reference signal from the hydrogen maser frequency standard, at DSS 13, into two signals. One of the signals is connected to the fiber-optic transmitter and the other signal is connected to the reference input to the phase stability analyzer. The signal going to the fiber-optic transmitter modulates the optical carrier and the resulting optical signal is transmitted to DSS 12, where it is connected to the other fiber, and returned to DSS 13. At DSS 13 the optical signal is detected to recover the 100-MHz RF signal, which is amplified to the required level and then connected to one of the other ports of the stability analyzer.

IV. Stability Analyzer

A block diagram of the stability analyzer is shown in Fig. 3. A 100-MHz reference signal derived from the hydrogen maser frequency standard is applied to the analyzer through an isolation amplifier. An RF power splitter splits the 100-MHz reference signal into two equal amplitude signals. An offset synthesizer offsets one of these signals by 1 Hz resulting in a frequency of 99,999,999 Hz. An RF mixer multiplies the 99,999,999-Hz signal and the 100-MHz reference signal and produces the difference frequency of 1 Hz, plus the phase noise of the signal being measured. This 1-Hz output signal passes through a low pass filter, which has gain, to a zero crossing detector. The signal out of the zero crossing detector is analyzed in a microprocessor which provides Allan variance data at 1, 2, 4, and 8×10^n seconds, where n is an integer $\geqslant 0$.

V. Measurement Method

The stability analyzer measured the frequency stability (Allan variance) of the output signal from the round-trip fiber-optic link, using the input signal to the fiber-optic link as the reference. The phase difference between the two signals was also monitored and recorded.

Figure 6 shows a simplified block diagram of the test setup. For this test all the terminal equipment and test instrumentation was located at DSS 13 and a second fiber, identical to the first, was used to complete the 14-km round-trip between DSS 13 to DSS 12 and back to DSS 13. It is important to note that the data gathered was for the entire round-trip including terminal equipment.

The noise floor of the measurement equipment was determined by bypassing the entire fiber-optic link and using a coaxial attenuator in its place to maintain identical signal levels to the test equipment. Figure 7 shows the resulting Allan variance data which is marked "N.F." (noise floor). Notice the deviation from a $1/\tau$ slope where $\tau > 10$ seconds. This is primarily due to thermal and vibrational characteristics of the test environment on the stability analyzer and test cables.

An existing clean-up loop with a noise bandwidth of 5 Hz was used at the output of the fiber-optic link to reduce the bandwidth and measured noise power of the received signal. The noise floor of the test system, with the clean-up loop only, was measured and is shown in Fig. 7 and is marked "C.U.L." (clean-up loop).

An additional measurement was performed using a short piece of fiber-optic cable at the test location in order to determine the stability of the terminal equipment only. This is shown in Fig. 7 by "T.E." (terminal equipment).

VI. Test Results

Figure 8 shows the Allan variance for the roundtrip fiber-optic link, including the clean-up loop. The $1/\tau$ slope portion of the graph where τ is less than 100 s is primarily due to the

signal-to-noise ratio of the fiber-optic link. For $\tau > 100$ s the Allan variance does not decrease at a $1/\tau$ slope as expected but shows a hump around 400-s averaging time.

The frequency stability of signals passing through cables which are subjected to temperature cycling is expected to be degraded. This degradation shows up on Allan variance plots as a hump usually between 100 and 1000 seconds which corresponds to the air conditioning cycling time. The time constant of the cable, the length of the exposed cable, and the magnitude of the temperature variation determine the magnitude of the hump. The hump is usually broad because the cycling time is not constant.

The cyclic phase change responsible for the hump in the Allan variance curve was observed and recorded. It appeared to be a result of temperature changes in the plenum at DSS 12. The air conditioning at this location has a cycle period of about 1080 seconds, and the peak to peak temperature variation is about 3 K. The length of the exposed cable in the plenum is about 45.7 m round-trip and the cable has a temperature coefficient of 7 ppm/K.

The expected phase variation as a result of this temperature change was calculated using the above values and, assuming zero time constant for the cable, the phase change in degrees as a result of a change in temperature is,

$$\theta = 1.71 \times 10^{-12} L \alpha T f_o \tag{1}$$

where

L = the affected length of cable, m

α = the temperature coefficient of delay of the cable, ppm/K

T = the change in temperature, K

f_o = the operating frequency

Evaluating this equation using the above values yields 0.164 deg, which is about twice the variation measured. However, the integration of the temperature variation as a result of the time constant of the cable could account for the difference. The time constant of this cable was calculated from this data as 5 min. This is not unreasonable since a coaxial cable of approximately the same size, but with more mass, has a time constant of ≈ 20 min.

To verify that this effect was actually observed, the phase of the round-trip signal was compared to the reference signal and monitored at DSS 13. The temperature in the plenum at DSS 12 was also monitored at the same time. A strong correlation was observed between the variation of temperature and the variation of phase. In the evening, when the outside temperature is lower, the air conditioning in the DSS 12 plenum is turned off and outside air is used to cool the building. During this period the temperature did not cycle and the observed phase variations at DSS 13 disappeared. This was a further indication that the observed phase variations at DSS 13 were a result of the temperature variations in the plenum at DSS 12. The plots of phase at DSS 13 and temperature at DSS 12 are shown in Figs. 4 and 5, respectively.

As mentioned before, the link was set up for one-way transmission of the hydrogen maser reference signal from DSS 13 to DSS 12 to provide a stable reference for DSS 12. The stability of the one-way trip cannot be measured because there is no independent reference at the far end of the link. However, it can be estimated for the $1/\tau$ region of the curve from the relationship between the Allan variance and the signal-to-noise ratio of the signal being measured (Ref. 6).

$$\sigma = \frac{1}{\omega\tau} \sqrt{\frac{P_n}{P_s}} \tag{2}$$

where

ω = the angular operating frequency

τ = the sampling interval

P_n = the noise power in the signal being measured

P_s = the signal power

Using the SNRs measured at DSS 12 and DSS 13 (110 dB/Hz and 85 dB/Hz, respectively) and the above relationship we estimate a theoretical improvement of 25 dB for the one-way trip for averaging times less than 10 seconds. This improvement will not be fully realized because the cleanup loop has a bandwidth of 5 Hz corresponding to a stability of only 1×10^{-13} for 1 second averaging times. A cleanup loop having the proper bandwidth is being designed.

It was also noticed that bending the fiber resulted in phase changes of several degrees. This was unexpected based on experiments performed earlier and the results of a literature search.

VII. Discussion

The experiment reported here has generated a number of new and interesting questions. Important questions pertain-

to why the delay through the fiber-optic link is affected so much by bending the fiber. According to the theory (Ref. 5) the change in delay of the fiber should be much smaller. One may speculate that the amplitude to phase modulation conversion in the measurement system could be responsible for the change in the delay, or it could be that changing reflections back into the laser changes its wavelength, resulting in delay variations due to dispersion in the fiber. A third possibility is birefringence in the fiber. However, the most probable cause of this group delay change is the optical equivalent of voltage-standing-wave ratio. We are currently engaged in the study of the effect to identify the mechanism responsible for it and ways to minimize it.

How stable is the buried cable? The signal-to-noise ratio of the laser, temperature variations, and floor vibrations appear to account for most of the frequency instability we measured. If this is true, we have not yet seen the noise of the buried fiber-optic cable and we must reduce these instabilities in order to see the cable instabilities. Increasing the time constant of the exposed fiber-optic cable and isolating the equipment from vibrations should improve the frequency stability of the distribution system.

VIII. Summary

A 100-MHz reference frequency from a hydrogen maser has been distributed 14 km over an unstabilized single-mode fiber-optic link with a stability of 1.5×10^{-15} for 1000 seconds averaging time. This link is providing an ultrastable reference signal to DSS 12 from DSS 13 over a distance of 7 km. This reference is more than 2 orders of magnitude better than the station Cesium beam reference normally used at DSS 12. This will permit coherent interferometry measurements to be made using the two stations.

This experiment has provided the data necessary to greatly improve the stability of reference frequency distribution systems; however, there is still much work to be done to achieve the ultimate goal of 10^{-18} stability for 1000 seconds averaging time.

Acknowledgment

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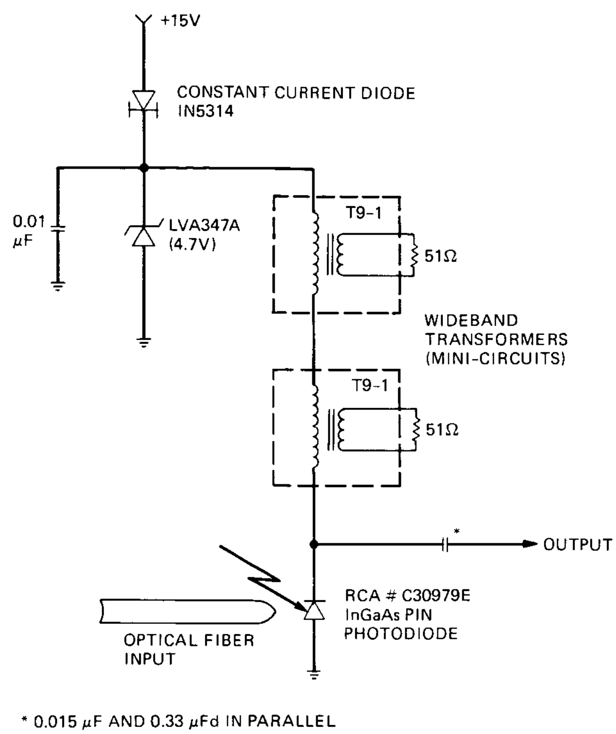

Fig. 1. Fiber-optic receiver schematic

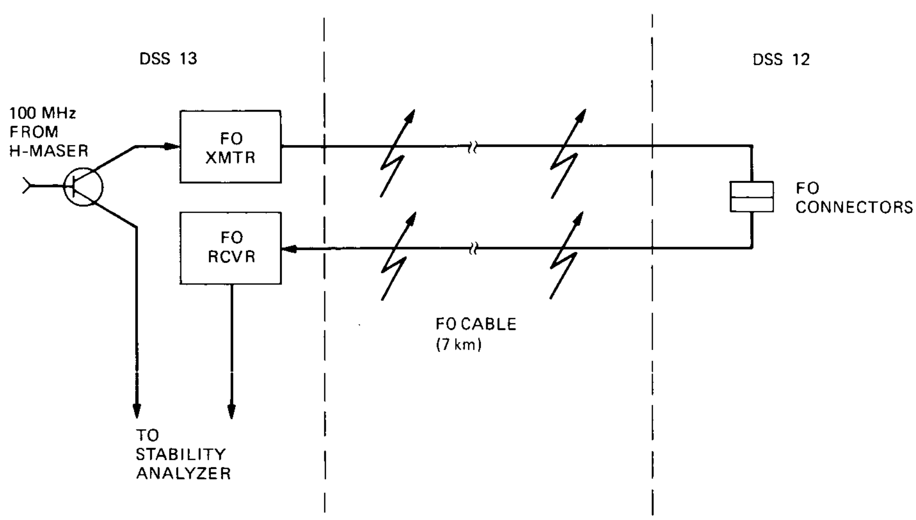

Fig. 2. Fiber-optic (FO) system configuration

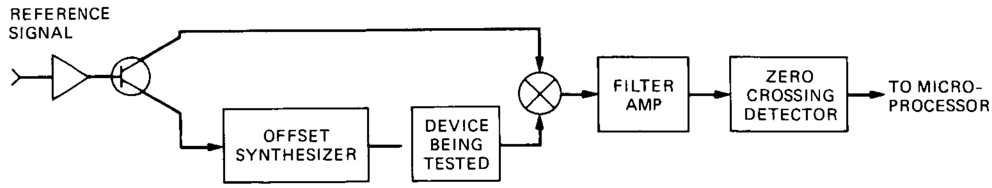

Fig. 3. Simplified block diagram of the stability analyzer

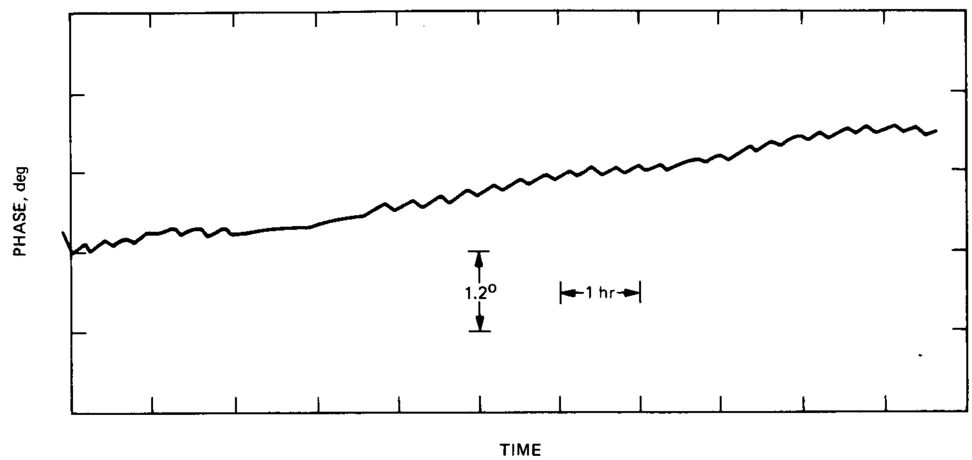

Fig. 4. Phase measured across the fiber-optic link

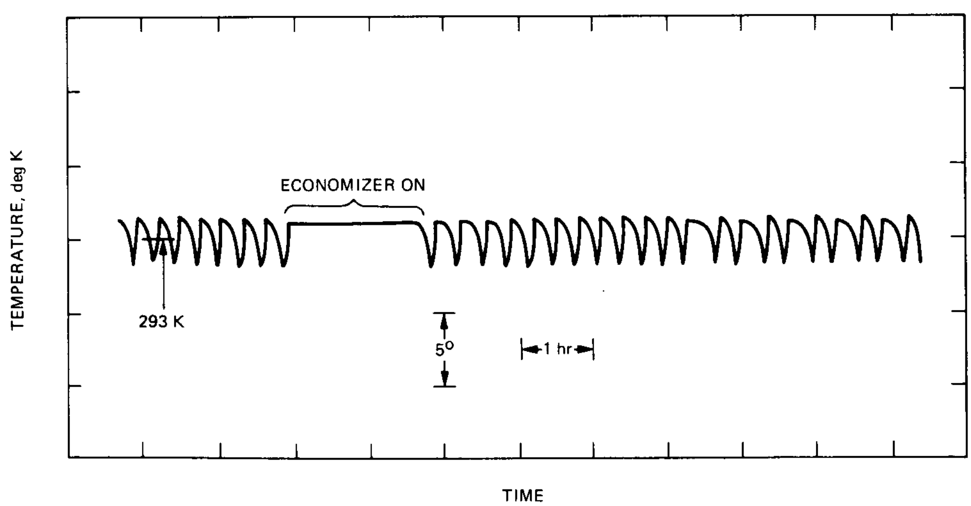

Fig. 5. Temperature measured in the Echo station plenum

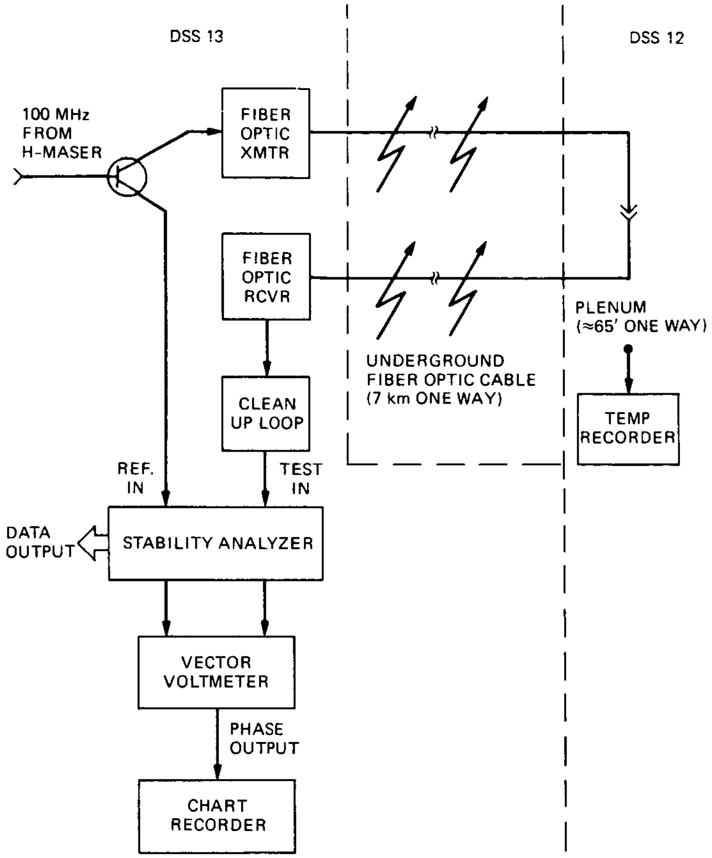

Fig. 6. Simplified block diagram of the test set-up

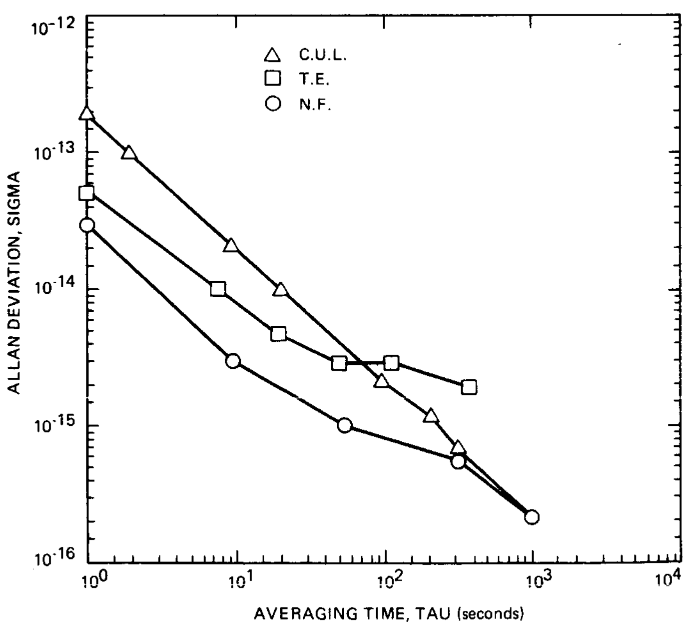

Fig. 7. Allan variance vs averaging time for the cleanup loop (C.U.L.), terminal equipment (T.E.), and noise floor (N.F.)

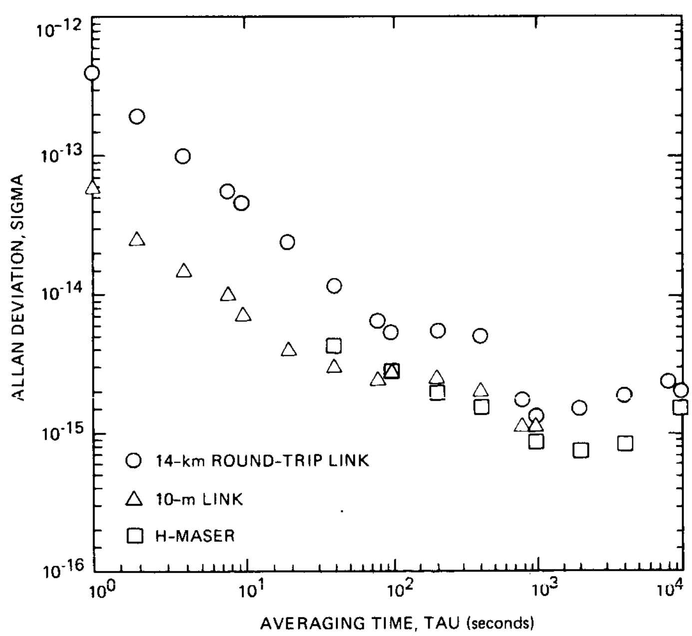

Fig. 8. Allan variance vs averaging time for the 14-km link, 10-m link, and hydrogen maser